Flexible Photovolaics for Fabric Structures

Final Report on Phase I SBIR

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Flexible Photovolaics for Fabric Structures

The Phase I technical objectives were fully met, demonstrating the feasibility of integrating Amorphous Silicon Modules into tent fabric and preparing for the Phase II tasks. The Phase I technical objectives were:

Phase I Technical Objectives

1. Identify candidate materials and processes for incorporating our flexible thin film PV modules into tent panels based on meeting physical requirements, durability, and expected costs.
2. Demonstrate feasibility by fabricating samples of the top candidates and evaluating these samples for their mechanical properties and processing scalability.

Materials search

Approximately 50 vendors & manufacturers were contacted for polymer materials suitable for the various layers needed to create a combination tent fabric panel/photovoltaic module system. A diagram of the layers needed for the structure is shown in figure 1.

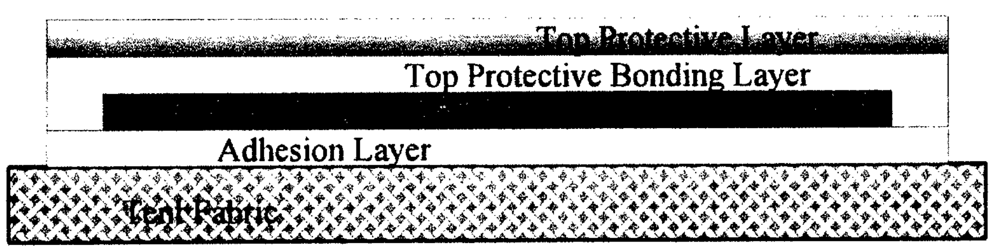

Figure 1. Diagram of the structure stack for combining a flexible photovoltaic module with a fabric tent panel. The photovoltaic module is bonded to the fabric panel by the adhesive layer while the top encapsulant/bonding layer protect the module from the environment.

The required top clear layers include a durable protective outer glazing (the "encapsulant layer") and a thermoplastic or pressure sensitive adhesive inner glazing (the "bonding layer") to bond the encapsulant layer to the flexible PV module. Encapsulant layers considered for this application included fluoropolymers, polyesters, polycarbonates, and polyurethanes. Some encapsulants require UV absorbing additives, while others do not. Bonding layers containing UV additives have been sought when possible. Bonding layer candidates include polyethylene, EAA (ethylene acrylic acid) copolymer, polypropylene, acrylic PSA, silicone PSA, clear epoxy films, and various acrylics.

In addition to the encapsulant and bonding layers, two other layers are required to complete lamination of flexible photovoltaics on fabric structures: the fabric substrate to be bonded to and the adhesive layer required for attaching the photovoltaic laminate to the fabric. Materials to be used as the fabric structure are composed of coated and non-coated wind and water-resistant materials. PVC coated polyester fabric was chosen as the default for the base layer because of it's history and suitability for fabrication of military tents. The adhesive materials that were examined include polyurethanes, nylons, polyesters, polyolefins and thermal set adhesives. Pressure sensitive adhesives (PSA's) acrylics, silicones, rubbers, and synthetics were also tested/evaluated for performance, price, and manufacturability.

Optical evaluation of materials

The first test carried out on the top layers were optical transmission tests. All samples in the ETFE class (i.e. Tefzel) showed extremely low absorption across the spectrum. Reflection appears to be about 3% per air/polymer interface. The PVDF class (i.e. Kynar) also showed effectively no absorption and a reflection of 3.5% to 4% per interface. The polyesters showed a little absorption, particularly in the blue and near UV. Reflection was roughly 6% per interface. Two of the polyesters showed very effective absorption edges at 400 nm, going from 87% transmission to 1% transmission very rapidly. These are very promising for protection of underlying susceptible adhesive layers from UV damage. The epoxy and EAA bonding layer films also showed low absorption. It is hoped that this will translate into good UV stability. The other bonding layers showed more absorption below 400 nm. Curves showing typical transmission spectra for ETFE's, PVDF's and stabilized polyesters is shown in Figure 2.

Bond strength and temperature limit tests

Prior outdoor test experience has shown that a top protective layer, even if it has high peel strength at room temperature, may fail over time under high temperatures. This takes the form of a slow creep or delamination. Because of that failure mode, a test procedure was developed to test mechanical bond strength of the top encapsulation system as a function of temperature. It is effectively a 90-degree angle peel test with a constant force applied.

In this test, a series of samples were prepared and placed under constant force in a test oven. The temperature of the test oven was stepped up in 5-degree centigrade (C) increments. Failure temperature was recorded for each system.

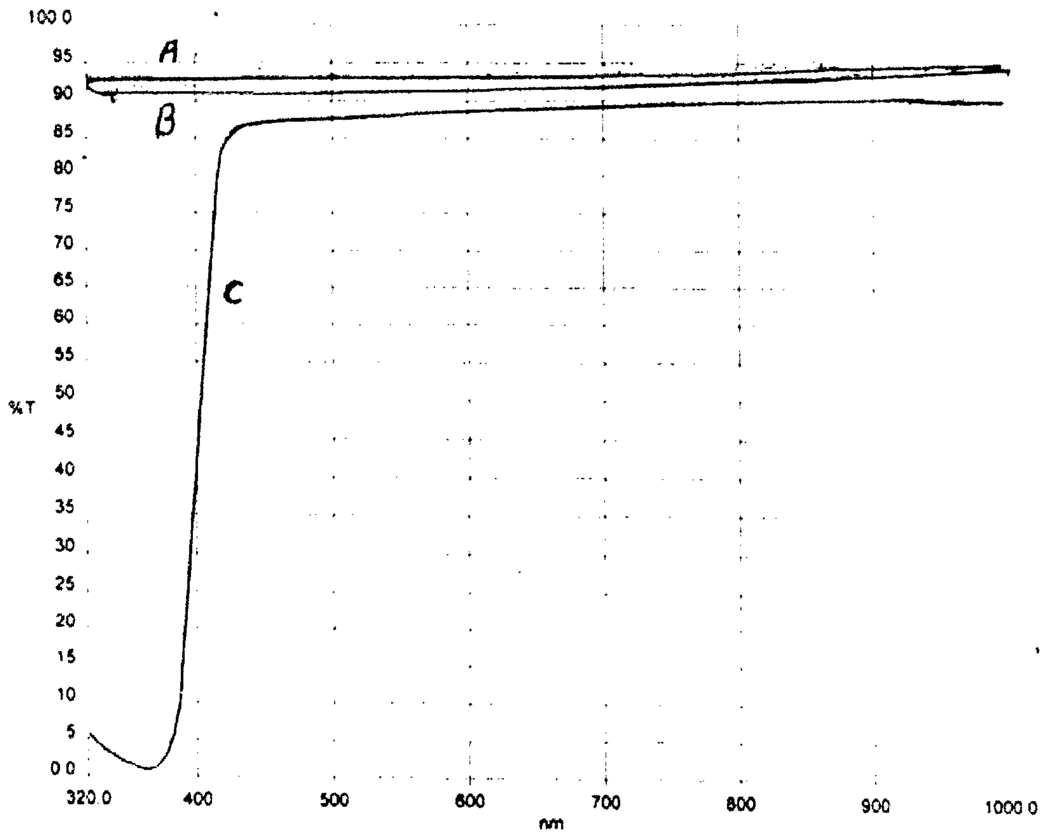

Figure 2. Transmission spectra for 3 classes of top encapsulant. The ETFE (A) and PVDF(B) are flouropolymers and are inherently UV stable. The polyester (C)is not inherently stable and has an additive which absorbs in the UV to provide stability for itself and underlying layers. This is responsible for the rapid drop in transmission around 400 nm. There is very little energy in the solar spectrum below 400 nm, so losses are minimal.

Initially, the samples of top encapsulant bonding layer were tested for peel strength and the temperature limit where peel strength failed against the solar module material. To make this evaluation, 1/2 inch wide test coupons were made up consisting of 2 strips of PV material bonded together face-to-face using the full range of adhesive candidates. These were set up on racks using a 90 degree angle peel configuration and a constant peel force. Peel distances were measured as the structures were subjected to successively higher temperatures. A survival threshold of 90C was chosen based on prior experience. Two candidates adhesives in addition to the EVA standard passed this test. These were the Scott EAA and the Dow thermally activated epoxy.

These passing bonding layer candidates were then tested with the full range of top encapsulant samples. In this test, structures similar to the ones with the PV samples were constructed. These had 2 encapsulant layers bonded face-to-face with the 3 surviving bonding layers (EVA, EAA, and Dow epoxy). Room temperature peel strength of these systems were measured as well as the temperature induced failure tests. Additionally, a number of vendor formulated combination encapsulant/adhesive layers were tested.

As a side issue, a new ETFE (Tefzel-like) was identified which has significantly improved peel strength in conjunction with EVA. Standard Dupont Tefzel/EVA has peel strength in the 3 to 4 Lb./in range while the new ETFE/EVA strength is in the range of 20 Lb./in. This improvement has the potential to eliminate one of the major failure modes of Tefzel/EVA. Optical properties of the new material are the same as Tefzel.

Bonding the modules to the PVC coated tent fabric proved more difficult than anticipated. Similar tests to those described above were carried out to test the bond strengths of the adhesive layer to the back of the modules and to the PVC fabric. This was done by bonding two strips of module, back to back with the various adhesives and bonding two strips of fabric face to face with the various adhesives.

Some adhesives bonded well to the fabric and some bonded well to the back of the module (a thin sputtered stainless steel layer), but no one adhesive bonded well to both materials. Tests were redone with various cleaning procedures, but the results were the same.

To overcome this problem, a slightly more complicated structure was developed. We concluded that we needed to use one material to bond to the back of the module and a second to bond to the PVC. The two adhesive layers then form a bond between themselves. Peel strength tests were carried out between the range of materials available which bonded to either the module backing or the PVC fabric. **The best peel strength for bonding the module to the fabric was achieved by a combination of Dow epoxy against the back of the modules and Bemis 5250 against the PVC .**

Summary tables of important results are shown below.

Test Material	Failure temperature (C)	Comment
SN 108	60	
D19073	104	
D19083	90	
M8142	60	
PX5332	60	
EVA(Std)	104	
PX1164	60	
Poly(std)	76	
S-EAA	104	

Table 1 Bond failure temperatures for top bonding layer candidates against the solar module. Tests were done with the test material bonding two solar modules face to face.

Laminant	Failure temp. w/EVA	Failure temp. w/EAA	Failure temp. w/D1973
K2800	60	130+	130+
Courtgard	125	60	95
STR Poly	125	60	60
Terephane	60	70	60
Halar	75	60	60
K740	60	60	130+
Tefzel	105	80	75
Florex	60	130+	95
Florex P	Mech failure	Mech failure	Mech failure
Isosolar	125+	80	100

Table 2 Maximum temperature before failure of bond between various to encapsulants and the 3 bonding layers which passed the bond strength test against the silicon solar module surface.

Adhesive material	Fail temp for stack	cold peel w PVC	cold peel w Courtgard	cold peel w Kynar	cold peel w Florex
B5209	100	27+	2	1	1
B5251	80	27+	1	1	1
B5250	100	27+	1	1	1
AF 300	65	27+			
301	75	27+	1.5	1	1
304	90	27+	5	1	
420	70	27+			
Eastman	65	2			

Table 3 Bond strength and failure temperatures for back adhesive materials. The failure temperature measurement is for a stack with the photovoltaic module material bonded to PVC coated fabric with the candidate adhesive material. While there were many adhesive materials with good bond strength to PVC coated fabric, none of them had good strength bonding to the back of the module or typical encapsulant materials. Likewise, none of the bonding layer materials which worked well with the module and encapsulant layer would bond to the PVC coated fabric.

Performance testing

Once the top set of candidate stacks were identified based on mechanical bonding and optical properties, tests were performed to evaluate the effects of these encapsulant stacks on device performance. Baseline I-V curves were taken on a group of modules before encapsulation and then incorporated into full stacks bonded to fabric. Performance tests were then performed on the completed stacks.

The most surprising result was a drop in fill factor for all device stacks fabricated with the Dow epoxy in direct contact with the module. The drop was up to 50% in some cases. The mechanism responsible for this decrease was determined to be an increase in the series resistance. This effect was surprising in that it had not been seen before with other bonding layers.

More detailed analysis of the devices showed that the top transparent conductor was being fractured by the differential shrinkage of the Dow epoxy and separated from the modules surface. This happened during the cool down after the lamination process. One of the major difference between the Dow material and other bonding layers is it's ridgidity. It is hard enough to be almost brittle. Evidently the ridgidity allows the material to put extreme stresses on the module during thermal cycling. Engineers from Dow have indicated that, additionally to the basic thermal expansion coefficient, there is a tensile factor engineered into the film during it's formation. This is incorporated as a aid to other typical applications of the product.

The Dow epoxy bonding layer was the first choice candidate based on mechanical behavior and optical performance. This effect on the zinc oxide, however, makes is unacceptable for direct contact to the face of the solar module. A modification of this primary candidate has been made to include a layer of EAA between the Dow epoxy and the face of the module. The Dow epoxy still is used to make a good mechanical bond to the top protective layer. This approach adds to the complexity of the stack, but maintains the excellent mechanical bonding behavior. One additional potential benefits of the structure is that the EAA can be applied to the face of the module that it earlier stage of the manufacturing process if desired. This would form a protective layer during later stages of module assembly, thus adding some extra flexibility to the processing sequence.

Long-term testing

A number of the structures were fabricated for long-term testing of the primary candidate module stacks and a number of alternative stacks. Full assemblies of modules bonded to PVC coated tent fabric were fabricated for long-term outdoor testing.

Test coupons of the front encapsulation structures were fabricated for accelerated UV testing. These coupons have the top protective encapsulant on the front and back with the bonding layer in between. These coupons have been sent to NREL for a number of long-term tests. These tests include high UV only, outdoor concentrated UV, and weatherometer tests. First results of these tests are expected in six months.

Prototype fabrication

Two prototype assemblies were fabricated which incorporate a number of full modules mounted on a section of tent fabric. The fabric sections were approximately 10 ft. by 31 inches which is comparable to one side of the roof section of a TEMPER tent system vestibule. This was chosen to allow the possibility of fabrication into a solar fly for this tent component to allow long-term testing. Eight module assemblies were laminated onto each section of fabric. The module assemblies were approximately 12 inches by 24 inches each in size. The modules were wired together in parallel. This assembly structure allows the fabric section to be fan folded into a compact unit for transport. This prototype will allow comparison of the fanfold concept to the roll up concept for future design guidance.

The prototypes were assembled at the same time that the functional test modules were fabricated, so they used the initial choice of the encapsulant stack which included direct contact between the Dow epoxy and the solar module. Thus, the performance of the prototypes is severely diminished as described above. This unfortunately limits the use of this prototype to testing the mechanical and handling behavior of the system.

Fabrication of the prototype was also used to gain in understanding of the manufacturing issues associated with incorporating the photovoltaic modules onto larger sections of tent fabric. A temporary lamination system was assembled which processed one module unit at a time. a significant base of knowledge was gaining regarding temperature control and lamination times for this type of system.

Conclusions on Top Layers

The EVA standard passed with all encapsulants as expected. Long cure time still makes this unattractive from a manufacturing standpoint.

The Dow epoxy passed with all encapsulant layers including the Kynar type materials and the polyester materials. Bond strength was extremely high with materials failing before bond failure.

The Dow Epoxy damages the transparent conductor layer of the photovoltaic device if put in direct contact.

The EAA passed with most of the Kynar type materials and the ETFE, but failed with the Polyester. It bonds well to the module face.

Two of the combinations also passed the tests. They are a combination of a Kynar type material and an thermal acrylic material. This is particularly interesting because the combination has a significant history of outdoor use and stability against UV.

Bonding of the module to PVC coated tent fabric is best accomplished with a double layer of Dow epoxy and Bemis 5250 adhesive.